Simple LC Bandpass Filters with Air Core Coils

13Oct08, update 16Oct08, Wes Hayward, w7zoi

The Problem

In the late 1960s I build a solid-state receiver that used toroids in all of the tuned circuits. The toroids were a departure from earlier slug tuned coils. I've never moved back. Although some solenoid forms have been used for VHF applications, or for some antenna matching networks, powdered iron toroids have been the backbone for all LC bandpass filters in my gear. I think that my experience is typical of folks building gear in the US, for the toroid cores are readily available, reasonably priced, and easy to use.

But our good fortune is not universal. Powdered iron toroid cores are next to impossible to obtain in many parts of the world. This prompted me to investigated a simple LC bandpass filter that used air core coils.

The role of coil Q

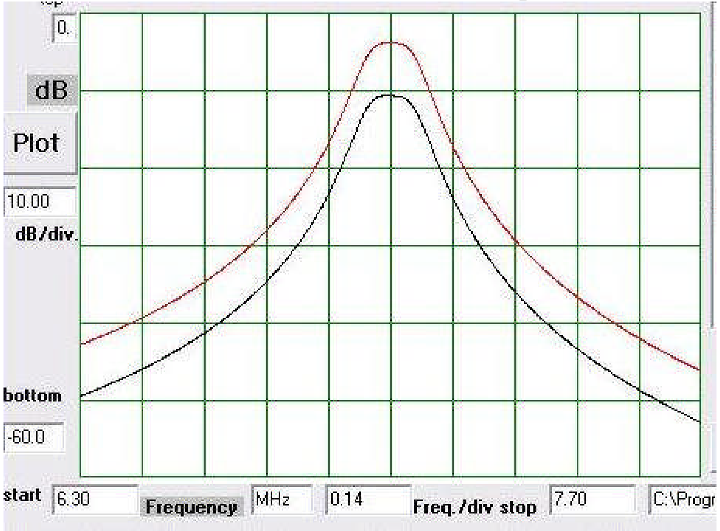
The term "Q," standing for quality factor, is used to describe components that are parts of tuned circuits. We often take the term to be nothing more than a casual figure of merit, something that would be nice, but is not necessary. This is not valid. Q is a numeric parameter that describes what we can and cannot realize when we build a filter.

Q is related to bandwidth. An *unloaded* Q of a tuned circuit is the center frequency divided by the bandwidth of that circuit. A 7 MHz tuned circuit with Q=100 would have a bandwidth of 70 kHz. But this parameter relates to the unloaded Q, which means that it describes the circuit when it is not connected to the rest of a system such as a transceiver. We designate the unloaded Q as Qu. Once we connect the network to other circuits, the net Q will always drop below the unloaded value.

Generally a double tuned circuit, which is a filter with two resonators or tuned circuits, will require an absolute minimum Qu that is double *f*/B where *f* is the center frequency and B is the final filter bandwidth. Assume that we wished to build a filter at 7 MHz with a final bandwidth of 70 kHz. That's a filter Q, Qf, of 100. An effective double tuned circuit would require Qu of 200 or higher to realize such a bandwidth. If Qu is not at least this high, the filter insertion loss will be excessive.

This requirement is not a rule of thumb that someone merely generated because it seemed to work. **Rather, this is the result of basic physics**. It is a direct result of *conservation of energy*.

Wider filters can use Qu with lower values. For example, if we had some 7 MHz resonators with Qu=100, we could build double tuned circuits with a filter Q of 50. Continuing the 7 MHz example, we could build a filter with a bandwidth of 7/50, or 140 kHz. Shown below are transfer functions showing 7 MHz filter responses. Two values for Qu were used to design the filters, Qu=100 and 200. The insertion loss is over 10 dB for the case of Qu=100, which is unacceptable for most applications.

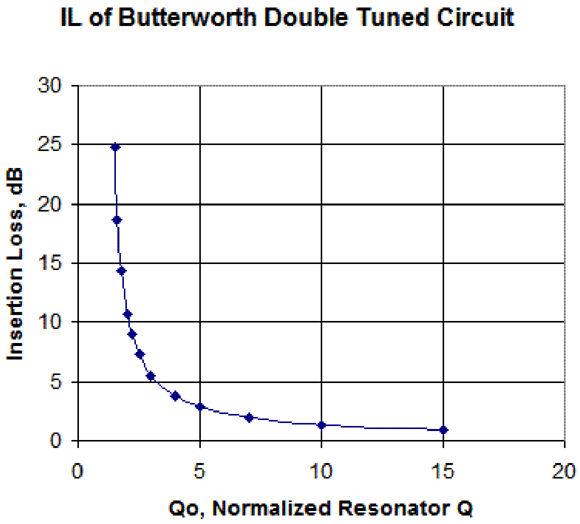


0.
10.00 dB/div.
bottom -60.0
start 6.30
MHz
0.14 Freq./div
stop 7.70
C:\Progr

Transfer functions illustrate the role of Qu. The upper curve has Qu=200 while the lower uses Qu=100. Both 7 MHz filters have a 3 dB bandwidth of 140 kHz.

We have assumed here that the Qu of tuned circuits is dominated by the Qu of the inductors, leaving the capacitors to be ideal. This is generally valid for HF filters with leaded capacitors. It may not be valid at VHF and is certainly a major consideration when SMT parts are used.

Shown below is a graph of double tuned circuit insertion loss versus normalized filter Q, q0. q0 is defined as Qu/Qf. For example, a 7 MHz filter with bandwidth of 70 kHz has Qf=100. If this is built from resonators with Qu=200, q0=2.0.



Insertion Loss depends on Q0, which is the ratio of Qu to Qf.

Hardware store washers as toroid coil forms

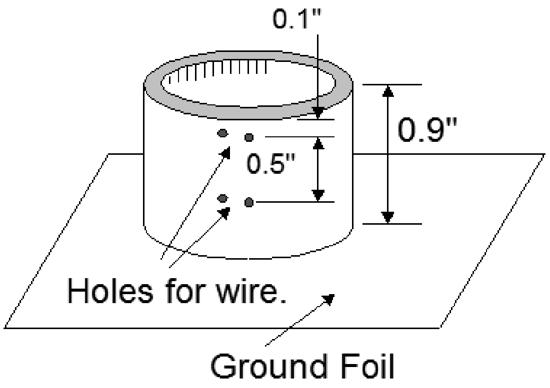
Some experimenters have built bandpass filters using toroid coils wound on washers from a local hardware store. These washers are intended for use in water valves. I was curious about the Qu of these coils when I first read of the method. Some washers were purchased at a local favorite hardware store, coils were wound, and Q was measured using the methods outlined in Chapter 7 of EMRFD. The best inductors I found had Qu of 82 at 14 MHz. This was a toroid with an outside diameter of 0.56 inch with a material that appeared to be Nylon, or a similar plastic.

A 14 MHz bandpass filter built with these inductors (Qu=82) would have an insertion loss of about 6 dB if the bandwidth was 0.5 MHz. Dropping the bandwidth to 0.25 MHz would send the IL to almost 30 dB. Higher Qu inductors would improve filter performance significantly.

PVC and Plastic Inductor based Filters

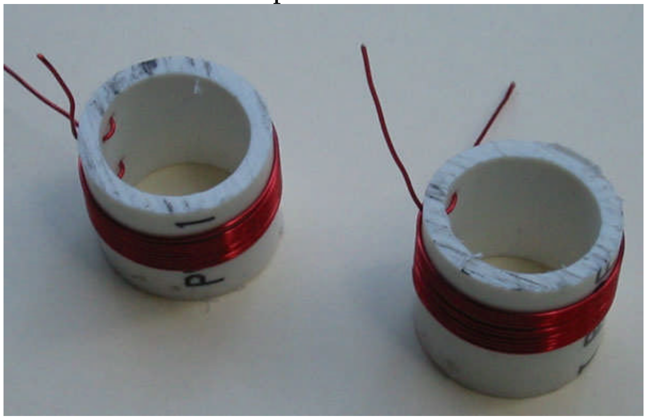
Having found that the hardware store washers were less than ideal, some solenoid forms were investigated. The first coils were wound on forms build from PVC pipe. The pipe I picked was marked as PW Eagle ¾ inch IPS SCH 40 48 PSI @73°F PVC 1120 ASTM D1785 UL Listed Coldwater Pipe 92FJ/UL. (It usually comes in 8 foot lengths, so there is a lot of room for data to be printed!) This was a thick walled pipe with an outside diameter of 1.042 inch and a wall thickness of 0.11 inch. There is nothing special about this pipe; it's just what I had on hand.

Although I was interested in high Q, I also wanted to build filters that were not excessively large and did not use overly large diameter wire. I settled on a form that was just under an inch long with the winding constrained to a half inch length near one end. This design would assure that the coil was not too close to a metallic surface, which could drastically alter the inductor properties. The form is shown in the following drawing.

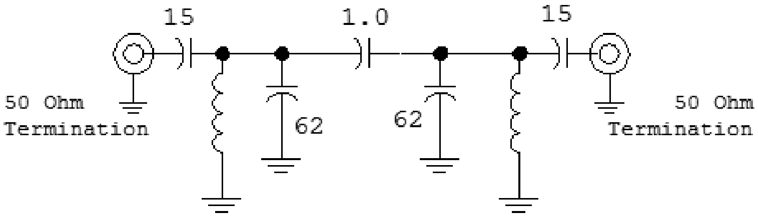


Coil Form made from PVC Pipe. The form is mounted to a ground foil with a wire through a single hole, not shown in the drawing.

The coil form dimensions were used to calculate the inductance of several coils using the standard ARRL Handbook formula. A 37 inch length of #22 enamel coated wire was then wound to form a 10 turn coil. The initial inductance was 3.5 µH. The Q was measured at 7, 10, and 14 MHz with the results Qu=173, 209, and 228 at the respective frequencies. The Qu increase roughly in proportion to the square root of frequency, which indicates that the dominant loss mechanism is copper loss. Dielectric loss in the form is minimal. A photo shows two of the coils.

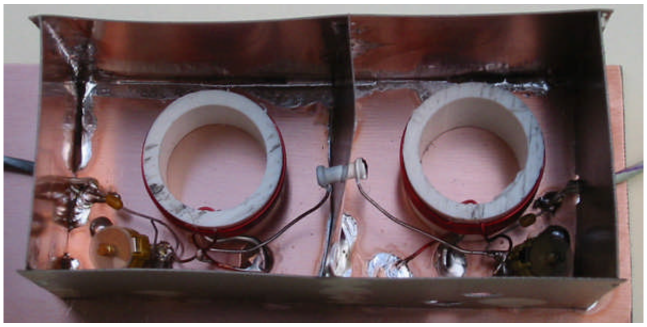

Coils wound on PVC Forms.

After measuring Qu with a coil mostly in free air, it was installed on a ground plane and surrounded by shields. The shields were 1.8 inches high, about twice the height of the coil form. The leads were extended out through small holes, allowing inductance and Q to again be measured. The inductance dropped to 3.2 µH while the Qu values decreased to 151, 181, and 200 respectively at 7, 10, and 14 MHz. A 10 MHz bandpass filter was then designed, shown below.



10 MHz bandpass filter using PVC coils with Qu=180. Bandwidth was 200 kHz.

This filter was then built, using plastic 65 pF trimmer capacitors to tune the inductors to frequency. A photo is shown below. The shields are 1.8 inch high, forming boxes approximately 1.5 x 2 inch. A notch in the bottom of the end shields allows small coax cable to enter the filter and a hole in the shield between sections provides a place for the 1 pF coupling capacitor.

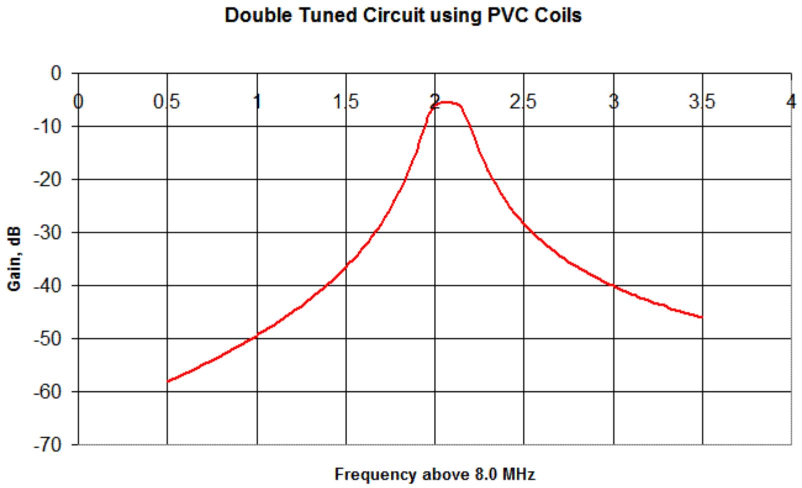


Completed LC bandpass filter using PVC pipe inductors.

Construction is no more critical than it would be with toroid coil forms. Shielding is, however, mandatory. Not only is it necessary to shield between the two coils so the only coupling is that from the coupling capacitor, but it is also important to confine the fields so they do not interact with surrounding circuitry. The shields I used were fabricated from very thin PC board (.018 inch) material that could be cut with scissors. The walls are slightly buckled, which was not a problem for an experiment. In spite of this, the finished filter is amazingly robust. No lid was used and would probably not be needed in a typical application.

One thought: When building filters of this sort, it would be useful to arrange the walls and shields to allow the components to be soldered in place prior to placement of a final wall. The wiring was a bit difficult as shown.

The measured response of this filter is shown below.



Measured response of the 10 MHz bandpass filter. Insertion loss is about 5 dB, consistent with simulations.

The LC filter described above used series capacitors to transform 50 Ohms to the impedance necessary to properly load the filter. Link coupling could also be used. The methods that might be used were outlined in a note on Transformer Coupled LC Bandpass Filters, June 2008. See http://w7zoi.net/Transformer%20Coupled%20LC%20Bandpass%20Filters.pdf

Conclusions and Other Thoughts

We can build LC filters with excellent performance without resorting to toroid forms. This occurs with high resonator Q, which is possible with volume. Even high Q can be achieved with larger wire size. I used #22 in the example filter, but the same form would have accommodated #18 wire. As the wire size increases, it becomes practical to use coils with no form at all.

PVC pipe was used in the experiment presented here. Other materials are just as useful. For example, the plastic film containers used by Kodak work well. Pill bottles also work well. There are numerous other possibilities that can be investigate. The key to such an investigation will be Q measurement.

The material presented here is certainly not new. Indeed, the methods are those of a bygone era of vacuum tubes, although multiple resonator tuned circuits were not nearly as common then as they are today. A lot has happened in the period between that bygone era and today. Technological evolution has brought us powder iron toroids that allow us to build filters that are much more compact than circuits using solenoid shaped coils. They also have lower loss, a result of the high Q offered by powdered iron cores.

The same period of perhaps 50 years from the vacuum tubes to today has brought an evolution in our understanding of filter design. We have a much better appreciation for the fundamentals. This allows us to design good filters, commensurate with the Q of the available resonators that we can build, no matter what the technology is that we might use to build them.

Consider an aside: It would be interesting to apply our present understanding of filters and other circuits to the technology that we had available in the 1950s. I recall one of the first RF transistors I had available to me when I was in high school was a 2N137, a 10 MHz F-t Germanium part. It would certainly have oscillated at frequencies at least as high as 10 MHz and might have worked as a receiver LO. We also had Germanium diodes that would have worked well as mixers. The LC filters described in this note would work well with those early circuits and the quartz crystals that we had then would have produced narrow crystal filters. The combination of these elements could have produced some very interesting and practical receivers, ones that would have held their own with other designs of the day. So much for digression.